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HOW MUCH SHOULD YOU PAY FOR THAT BOX

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TECHNICAL REPORT

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HOW MUCH SHOULD YOU PAY FOR THAT BOX?

PRESIDENTIAL ADDRESS
BY

CHARLES O. HOPKINS
HUMAN FACTORS SOCIETY

ARL-74-11/AFOSR-74-8
OCTOBER 1974

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PREPARED FOR

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

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I

ACKNOWLEDGMENT

This paper was prepared for presentation by the author as his Presidential Address to the Human Factors Society at the eighteenth Annual Meeting in October 1974. The paper is concerned with a general problem that has been brought into focus for the author by the results of several different lines of research that are a part of an ongoing research program at the Aviation Research Laboratory (ARL), Institute of Aviation, University of Illinois at Urbana-Champaign. The program is sponsored by the Air Force Office of Scientific Research, the Office of Naval Research, the Federal Aviation Administration and the Air Force Avionics Laboratory. The principal issues considered in this report are most directly related to some of the research tasks comprising the part of the ARL program sponsored by the Air Force Office of Scientific Research. Dr. Charles Hutchinson, Program Manager, Life Sciences Directorate, is the Program Monitor for the United States Air Force.

HOW MUCH SHOULD YOU PAY FOR THAT BOX?

Presidential Address by

Charles O. Hopkins, President

Human Factors Society

1973-74

Captain Rhodes noted that all his aircraft fly like aircraft. 707s, for example, fly like 707s. His simulators do not fly like aircraft and my simplistic answer is that the reason they do not fly like aircraft is they are not aircraft. The simulator is fundamentally a box sitting on the ground (Tait, 1972).

These remarks are quoted from a commentary at a Simulation Subcommittee Workshop sponsored by the Air Transport Association. Many millions of dollars have been spent and are being spent now for aircraft simulators. An airline's L-1011 aircraft simulator cost $2.3 million and the F-4J aircraft simulator for the Navy cost $5 million (Comptroller General of the U.S., 1973). Many more millions of dollars have been programmed to be spent. Development contracts totaling $31 million were awarded by the Air Force in 1971 and 1972 to build two experimental simulators (Comptroller General of the U.S., 1973) and that was just a beginning.

Why is so much money being spent for simulators? Quite obviously because there is a widespread belief that simulators are useful and that their usefulness justifies their cost. Yet, the vice president and director of engineering of a company that manufactures and sells simulators referred to the simulator as *fundamentally a box sitting on the ground.* How does it happen that the *box* can cost so much and that some customers are willing to pay the exorbitant cost? Before grappling with the answers to these questions some background is necessary.

USES FOR SIMULATORS

The uses for aircraft simulators that are most directly related to human factors are ones concerned with man-machine interface research and with crew training.

Research

Man-machine interface research frequently is performed with simulators rather than with aircraft. Use of a simulator permits much more precise control over experimental conditions and permits relatively easy systematic variation of conditions when required. In most kinds of research, use of a simulator provides a high degree of safety as compared to use of an aircraft. Because certain aspects of a flight mission that are not relevant to the research need not be flown in a simulator but would, of necessity, be required in an aircraft, time can be saved. The saving in time can be translated directly to a saving in money. Furthermore, additional dollars may be saved if, as can be the case, the acquisition, operation, and maintenance costs are lower for the simulator than for the aircraft.

A disadvantage to the use of a simulator rather than an aircraft for aviation research is the uncertainty about the validity of generalizing results from simulator to aircraft. For example, experiments involving flight attitude and steering guidance displays show that different simulator motion conditions not only can result in absolute differences in performance level when compared with flight performance, but also can result in different orders of merit among displays (Jacobs, Williges, and Roscoe, 1973; Williges and Roscoe, 1973).

Training

Many advantages have been presumed, inferred, claimed or substantiated for the use of simulators in pilot training. The most timely advantage asserted for the use of simulators over aircraft is a subsidiary benefit -- helping to ease the fuel shortage. This might apply not only to training *per se* but also to flying for maintenance of proficiency.

The most unusual advantage to be derived from use of a simulator for training is to be found in the cases in which it may be impossible to train the crew members in the actual vehicle during a mission. Indeed, the most glamorous and most widely publicized uses of simulator training were for space vehicle missions. In terms of the overall results, apparently these were highly successful uses of simulators. However, by virtue of the structure of astronaut training programs, it is difficult to determine just what to attribute to the simulator training as opposed to other aspects of the training programs. Also because of the national commitment to be the first country to place a man on the moon, the astronomical costs associated with simulators were not a major consideration.

The claimed advantages of simulators frequently cited for training are in the areas of cost, safety, efficiency, and effectiveness. However, some of these are equivocal.

Cost. Simulators *can* cost less to acquire, operate, and maintain than their counterpart aircraft. We have already referred to the exorbitant acquisition costs of some simulators. How do the operational costs of simulators and aircraft compare? Some simulators fare better in this comparison. An average cost per hour to operate the A-7 attack aircraft or the F-4 fighter aircraft is $853. The hourly cost to operate the simulator for each of these aircraft is about $80 (Comptroller General of the U.S., 1973). It has been estimated that it costs about $4,000 an hour to operate a Boeing 747 aircraft and about $400 an hour to operate the 747 simulator (Roscoe, 1974).

Some simulators are expected to fare considerably less well in an operational cost comparison with aircraft. It has been stated, possibly with tongue in cheek, but nevertheless, with at least some factual basis, that operation of a simulator now under development is expected to cause a brownout in a neighboring town and the surrounding area.

In spite of outstanding examples to the contrary -- notably simulators that are extremely complex in concept and design -- simulators not only *should* cost less to maintain than their counterpart aircraft, but

also *should* require less down time as a result of malfunction, and thereby produce less interference to a smoothly operating training program.

In stark contrast to the comparative costs quoted previously for operation of aircraft and their counterpart simulators is the statement by Caro (1973, p. 503):

> *In many pilot training programs, simulators are used as an adjunct to training conducted in flight. Their use is intended principally to effect a reduction in the overall cost of flight training, but in many instances (in fact, in almost all military training programs) there is little evidence that simulators have led to reduced training costs. In one such program, synthetic training was shown to add to the cost of pilot training without demonstrable transfer of training benefits* (Isley, Caro, and Jolley, 1968; Jolly and Caro, 1970).

It must be concluded that simply using a simulator that costs much less per hour to operate does not guarantee that the simulator training program will be cost-effective as compared to an aircraft training program.

Safety. A simulator provides a much safer environment for training normal flight procedures and maneuvers. Even more importantly, simulator training can provide the opportunity for a crew member safely to experience the consequences, up to the point of catastrophe, of inappropriate performance or operation. Closely related to this, the use of a simulator also provides an opportunity for training emergency procedures that would be dangerous if employed in aircraft.

Efficiency. Simulators can provide more efficient training than can be realized with aircraft. Initial conditions can be set up for teaching specific maneuvers or operations without requiring the performance of all of the mission phases that must precede them in the flight situations. Simulators can be and sometimes are used for training on a 12 to 18 hour-a-day schedule. They may be used for training regardless of weather conditions. In many cases simulators provide opportunity not available or feasible in aircraft to train the crew members simultaneously.

Effectiveness. An implicit assumption that underlies all of the preceding discussion of the advantages of simulators for training is that some transfer of training can take place from the simulator to the aircraft. It doesn't matter how low the cost, how safe the operation, how efficient the scheduling of trainees and presentation of training problems, if what is learned in the simulator doesn't transfer to the aircraft.

Valverde (1973) has reviewed the research on transfer of training from flight simulator to aircraft and concluded that the sometimes contradictory results may have been due to variables which were not assessed in the experiments. However, there seems to be a preponderance of evidence now that when used in well-designed training programs by flight instructors who are highly motivated, simulators and even mockups are very effective training adjuncts (Caro, 1971, 1972; Creelman, 1959; Flexman, Matheny, and Brown, 1950; Flexman, Roscoe, Williams, and Williges, 1972; Flexman, Townsend, and Ornstein, 1954; Ornstein, Nichols, and Flexman, 1954; Payne, Dougherty, Hasler, Skeen, Brown, and Williams, 1954; Povenmire and Roscoe, 1971, 1973; and Prophet and Boyd, 1970).

Selection and Proficiency Assessment

Simulators may be used not only for training and maintaining proficiency but also for predicting future success in training (selection) and evaluating the current effects of past training (proficiency assessment).

The McDonnell-Douglas Corporation, under contract to the Air Force Human Resources Laboratory, has been investigating the usefulness of a single-engine, light aircraft simulator for screening of candidates for the Air Force undergraduate pilot training program. The purpose of the research is to determine whether measures of student pilot performance during a five-hour minicourse of simulator training can be used to predict future flight training performance. The Human Resources Laboratory has been conducting an investigation with similar objectives using a light, twin-jet, aircraft simulator. Results from these studies have not been published.

Airlines, with the permission of the Federal Aviation Administration, have been using simulators for transition training since 1967. In this context, the Federal Aviation Administration uses simulators for certain proficiency evaluation tests of commercial airline pilots. Airlines have not made public data on the predictive validity of simulator performance. Koonce (1974) has just completed a comprehensive, large-scale experiment to determine the effects of ground-based aircraft simulator motion conditions upon prediction of pilot proficiency. For the best of the simulator motion conditions used, he obtained a coefficient of correlation of 0.724 between measures of performance in a simulator and a corresponding light, twin-engine aircraft.

COST-EFFECTIVENESS OF SIMULATORS

The answer to the question *How much should you pay for that box?* depends upon how and for what purpose you plan to use it. Furthermore, fundamental to each potential use is the requirement to answer the question, *Should it be used?* In simplest terms, a simulator should be used in a training program when it is cost-effective to do so. The cost, safety, and efficiency factors related to simulator training that have been described can be expressed in terms of dollars. It has been indicated that effectiveness of simulator training is to be evaluated in terms of transfer to the airplane.

The traditional measure of transfer of training, *percent of transfer* is not adequate for evaluating the effectiveness of a simulator training program because it does not take into account the amount of simulator training. Transfer is expressed only in terms of the amount of aircraft training that might be saved regardless of how much simulator training occurred. Clearly, this is of little value for the determination of cost-effectiveness. The real concern is with a comparison between the cost of a unit of simulator training time and the cost of flight time for which the unit of simulator training may be substituted.

Roscoe (1971, 1972) has developed a measure, the incremental transfer effectiveness ratio, which reflects the fact that successive increments of simulator training yield diminishing transfer to flight. Eventually, an increment of simulator training would

provide so little transfer that the flight time saved thereby would cost less than the next increment of simulator training. The use of the simulator beyond this point would not be cost effective.

Factors that contribute major costs to simulator training programs may or may not contribute to the effectiveness of such programs. The correlation between the cost and effectiveness factors may be far from perfect. In certain cases there may even be a negative relationship between effectiveness and the inclusion of a costly feature.

Effectiveness as a Function of Training Procedures

The single most important factor that influences the effectiveness of a simulator in a training program is how it is used. Almost 25 years ago Williams (1951) pointed out that the results obtained from a simulator depend a great deal upon how it is used. Twenty-two years and some almost incredible engineering developments later the following statements were made:

> *It is not at all surprising that flight simulators are built as realistically as possible. It is not surprising, either, that pilot-training program designers and administrators have tended to rely upon such realism to assure adequate pilot training. Too often many of these individuals appear to forget that the simulator does not train.* It is the manner in which the simulator is used that yields its benefit (Caro, 1973, p. 509).

Physical Simulation vs. Psychological Simulation

Given a well-designed training program and competent, motivated instructors and students, what other factors contribute to the effectiveness of a simulation training program? Certainly some of the characteristics of the simulator should be significant. Muckler, *et al.* (1959) distinguished between *physical simulation* which is concerned with the fidelity that may be achieved between the flight training device and the operational aircraft, and *psychological simulation* which is concerned with the ultimate criterion of any synthetic training device: the training value that results from the use of the device.

Much of the development in aircraft simulators has been dominated by the apparent attitude that *more is better*. This led to striving both for successively higher degrees of *physical* simulation including more visual, motion, and auditory cues, and for successively greater fidelity of *physical* simulation.

> *As the degree of engineering simulation* [degree and fidelity of physical simulation] *increases, the costs rise at an increasing rate. ... A trainer need not be an exact replica of the operational equipment to have training value. The most important consideration is its degree of transfer to the real tasks* [psychological simulation] (Valverde, 1973, p. 511).

For at least 15 years others who have been involved both in research and training functions have also questioned the necessity and desirability for universally high degrees and fidelity of *physical* simulation:

> *It has been suggested that deliberate differences between the simulator and the aircraft may result in greater training benefits than an exact simulation* (Muckler et al, 1959, p. 12).

> *In some instances, these devices incorporate deliberate deviations from realism in attempts to improve, from the transfer-of-training standpoint, upon the relatively poor learning environment of the design-basis aircraft* (Caro, 1973, p. 504).

> *... training devices are not exact physical replications of all aspects of the operational jobs for which training is intended. The reasons for such departures from perfect fidelity are: (1) Training-effectiveness -- it is contrary to good training practice to try to make training an exact replica of certain real jobs* ...(Blaiwes, Puig, and Regan, 1973, p. 524).

Simulator Fidelity and Motivation

Many experienced pilots genuinely believe that the more a simulator responds and *feels* like an airplane, the greater its benefit as an aid to training and proficiency maintenance. Pilots love to fly. If they can't fly in the air, they want to experience the closest thing to it on the ground. Flexman (1950, p. 23) has suggested:

> *Fidelity of simulation can operate as a motivational variable. If the simulator looks, acts, and sounds like an airplane, then the trainee is more likely to be convinced that practice will be beneficial to him. The problem is to determine the extent to which varying degrees of fidelity of simulation yield varying degrees of motivation.*

This same subject was considered recently by Huddleston and Rolfe (1971, p. 145):

> *Motivational fidelity (where the simulator feels like the real thing in all psychological senses of the word) may be unattainable. Statically and dynamically the simulator will have to be substantially complete, so that motivational fidelity is likely to come at the end of the cost "spiral."*

There is evidence to support the view that increasing fidelity of simulation in certain ways does have an effect upon performance in the simulator. Koonce (1974) showed that experienced pilots perform better in a simulator with motion cues than without motion cues. This finding could be related to the functioning of the motion cues as a motivational factor or as an alerting factor. If the former is the case, it might be expected that any fidelity-related motivational effect would be different for student pilots with no previous aircraft flight experience. The real issue, however, is not how fidelity affects performance in the simulator -- whether through motivational effects or otherwise -- but how degree and fidelity of simulation affect transfer from the simulator to flight in the aircraft.

Simulator Fidelity and Pilot Acceptance

The factor of "pilot acceptance" frequently is cited as a requirement for providing a high degree

and high fidelity of simulation. This is largely a myth that has been fostered and perpetuated by those interested in development of more complex and more costly simulators. There is no evidence to show that pilot acceptance of simulators is a significant problem. Although airline pilots retain a provision in their contracts that permits them to take a flight check in an aircraft if they fail to pass a simulator check, this provision is rarely exercised. Even if pilot acceptance of simulators were a potential problem, certainly we know enough about the management of reinforcement contingencies in learning to integrate simulator training effectively into a program in a manner that will achieve *pilot acceptance*. For the beginning student pilot, *acceptance* of considerably less than perfect fidelity in the simulator should be possible if flight in the aircraft is made contingent upon achievement of specified levels of performance in the simulator.

SIMULATOR FIDELITY AND TRANSFER OF TRAINING

The most extensive engineering development being done to increase the fidelity of physical simulation is perhaps in the areas of motion and visual systems. Certainly these two areas are among the most costly. Are the increasingly higher costs of achieving greater fidelity of physical simulation accompanied by increasing levels of psychological simulation (transfer of training)? There is no completely satisfactory answer to this question yet. However, some relevant data are available in the case of motion, and additional research is in progress.

Simulator Motion and Transfer of Training

Valverde (1973) has reviewed the transfer of training studies done with flight simulators through 1971. Included in this review are a handful of studies that were concerned with one or another aspect of motion (Townsend, 1956; Wilcoxon, Davy, and Webster, 1954; Ruocco, Vitale, and Benfari, 1965; and Ruocco, Klier, Gage, and Vitale, 1970). However, none of these studies provided any data on the effect of training simulator motion upon subsequent performance in an aircraft.

Additional studies concerned with various aspects of simulator motion have been done since the period covered by Valverde's review (Bray, 1973; Jacobs, Williges, and Roscoe, 1973), but it was not until very recently that the first experimental research was performed that provided information about transfer of training to aircraft flight performance as a function of the type of motion used during simulator practice. The research (Koonce, 1974) was designed to answer other questions, but as is frequently the case with well-conceived and well-executed research, the results provided some serendipitous information.

Major Jefferson M. Koonce, now a member of the faculty of the Air Force Academy, performed the research at the University of Illinois as the basis for his Ph.D. dissertation. The experiment was designed to investigate the effects of ground-based simulator motion conditions upon prediction of pilot proficiency. A total of 90 pilots with both multi-engine land and instrument ratings but with widely varying levels of experience and currency performed a simulated flight mission in a Link GAT-2 general aviation trainer on each of two days and then flew the same mission in a light twin-engine Piper Aztec aircraft the third day.

Experimental conditions for three groups of 30 pilots differed in terms of simulator motion. The simulator is equipped with a two-degree-of-freedom motion system (pitch and roll). One group performed with no simulator motion. A second group performed with sustained linear, scaled-down analog simulator motion. With this motion condition, as the simulated aircraft enters a turn, the simulator cab is angularly displaced in the direction appropriate for the turn and maintans an angular displacement proportional to the bank angle being simulated until such time as a change in bank attitude is initiated. A third group performed with *washout* motion. This provides the same roll and pitch acceleration cues as does the sustained motion, but while steady-state flight attitudes other than wings level are simulated, the simulator cab is returned to the neutral position at an angular displacement rate that is below the pilot's vestibular and kinesthetic thresholds for acceleration.

The mission consisted of five maneuvers representative of ones usually performed under instrument flight rules (IFR) without reference to the outside world and five maneuvers usually performed with outside visual contact under visual flight rules (VFR). In the simulator all of the maneuvers were performed without outside visual reference.

The results of this experiment provided an enormous amount of information on many aspects of measurement and prediction of pilot proficiency in simulators and in aircraft. However, this account is restricted to a few of the major findings concerned with the effects of simulator motion conditions.

Simulator motion facilitates performance in the simulator. The group with the no-motion condition consistently had higher error scores than the two motion-condition groups.

A high degree of prediction of flight proficiency of pilots with multi-engine land and instrument ratings can be made from ground-based simulator performance. The coefficients of correlation between performance measures on the second simulator mission and the aircraft mission were quite high for all three simulator motion condition groups. All were reliable at better than the 0.01 level of confidence. The highest predictive validity ($\underline{r} = 0.724$) was obtained with the sustained motion condition.

The serendipitous result referred to earlier is concerned with the effect of simulator motion conditions upon transfer of training to aircraft flight performance. All three groups showed significant improvement in performance between the first and second day in the simulator. In view of the wide differences in experience levels of the pilots and the lack of currency of many of the pilots (some had not flown in many years and some had never flown a lazy eight, chandelle, ADF instrument approach, or ILS instrument approach) it seems reasonable to interpret the improvement in simulator performance as learning. Therefore, the two simulator missions can be considered as training sessions for some and as refresher sessions for others.

Did the simulator training transfer to aircraft flight performance? All three groups showed significant improvement in performance between the second simulator mission and the aircraft mission. Either the airplane was easier to fly than the simulator or there was transfer of training from the simulator to the airplane. Although the differences among performances of the three groups in the aircraft were not statistically reliable, the disproportionate

improvement of the no-motion group strongly suggests differential transfer. Certainly, there is no evidence that simulator motion of either of the two types used enhanced transfer of training from the simulator to the aircraft. On the contrary, it may very well be the case that with simulator motion, pilots learn to respond to acceleration cues that may not be present in aircraft flight because much aircraft motion involves accelerations that are below detection threshold.

An experiment specifically designed to measure transfer of training from simulator to aircraft as a function of simulator motion conditions is being performed by Robert S. Jacobs as his doctoral research at the University of Illinois. A control group of beginning student pilots is being trained entirely in an aircraft. Three groups are being given simulator training under different motion conditions prior to transferring to the aircraft. These include no motion, normal washout motion, and directionally uncorrelated washout motion. The different simulator motion conditions are intended to permit evaluation both of the possible alearting function and the directing function of motion.

FUNDAMENTALLY A BOX -- WITH TRIMMINGS

I would not consider the money being spent on flight simulators as staggering if we knew much about their training value, which we do not. We build flight simulators as realistic as possible, which is consistent with the identical elements theory of transfer of Thorndike, but the approach is also a cover-up for our ignorance about transfer because in our doubts we have made costly devices as realistic as we can in the hopes of gaining as much transfer as we can. In these affluent times, the users have been willing to pay the price, but the result has been an avoidance of the more challenging questions of how the transfer might be accomplished in other ways, or whether all that complexity is really necessary (Adams, 1972, pp. 616-617).

How much should you pay for that box? It depends upon (1) your purpose in using it and (2) your method of using it. These factors will establish its necessary features, which determine its cost and its training effectiveness. Cost effectiveness has not been demonstrated for all the *bells and whistles* that come as standard trimmings on our current flight training simulators.

Many of us who are professionally involved with the use of simulators in research and training are gravely concerned about the effects of some of the current activities in developing and selling simulators. The acquisition of simulators that cost several times as much to own and operate as their counterpart airplanes is certain to produce a backlash. Such a reaction will set back the desirable use of cost-effective simulators in reasonable research and training programs.

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